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SOIL PERMEABILITY DETERMINATIONS FOR USE IN SOIL AND WATER CONSERVATION

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SOIL PERMEABILITY DETERMINATIONS FOR USE IN SOIL AND WATER CONSERVATION[1]

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INTRODUCTION

Soil permeability may be defined as the capacity of the soil to transmit water and air. It can be measured quantitatively in terms of percolation as the rate of flow of water through a unit cross section of soil in unit time per unit hydraulic gradient under specified temperature. Rates of percolation are usually expressed in inches per hour. Permeability may be judged by examining the visible soil characteristics.

A knowledge of the rate of movement of water through each significantly different soil horizon has many uses. The amount of water a given soil can transmit during a single rainstorm or succession of storms is governed by the permeability of the soil, including its infiltration rate. Runoff is regulated to a great extent by the rate at which water enters the surface soil and percolates to lower depths. In other words, soils which take and transmit water very slowly will give high runoff whenever rains of high intensity and long duration occur. Thus permeability and infiltration data are valuable in over-all planning for irrigation, drainage, erosion control, and flood control.

Information on soil permeability is indispensable to sound planning of drainage and irrigation measures for individual farms. For example, in planning and developing drainage systems, if the permeability of the subsoil horizons is slow or very slow, a tile system may not be practical or feasible, and open ditches may be needed to handle the excess surface water. On the other hand, where percolation rates range from moderately slow to moderate, a tile system will function properly. Obviously, the thickness of each horizon and its percolation rate must be taken into consideration in determining the size, depth, and spacing of tile.

The effective permeability of the entire soil profile, which must be calculated on the basis of the permeability of the different horizons, is highly important in laying out main canals, laterals, and small feeder runs of irrigation systems. Information on the

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[1]The authors used permeability data and reports of field observations obtained by many technicians of the Soil Conservation Service. These data and reports, and many suggestions regarding the preparation of the paper, are gratefully acknowledged.

percolation rates for different horizons, including infiltration at the surface, makes it possible to determine the proper rate and the most satisfactory manner of applying irrigation water from the standpoint of conserving both soil and water.

The selection of sites for farm ponds and reservoirs and their construction should be based on adequate information on the permeability of the soil at the proposed dam and reservoir site and in the drainage area above the dam. This information in conjunction with rainfall, evaporation, and evapo-transpiration data, is helpful in calculating the expected water supply for different seasons of the year. Data on permeability of the different soils and for segments of a large watershed are useful in estimating the peak rates of runoff to be expected from both small and large watersheds.

It has been found that the permeability of many soils can be modified by cropping and cultural operations. For example, the growing of deep-rooted legumes, application of straw mulches, and deep tillage have markedly affected the rate at which water enters the soil and percolates to lower depths. Advantage is taken of these findings in selecting soil and water conservation practices that are best suited for each farm and field.

BACKGROUND OF SOIL PERMEABILITY DETERMINATIONS

Much progress has been made in the development of techniques and equipment for measuring soil permeability since the first investigations of permeability were made several years ago. However, only since 1946 have permeability determinations been carried out as a part of soil conservation operations. At that time it was recognized that quantitative ratings of soil permeability were needed for such classification terms as ''very slow,'' ''slow,'' ''moderately slow,'' ''moderate,'' ''rapid,'' etc., so that descriptive classes would have a uniform meaning on a national scale.

Recognizing the importance of soil permeability information in classifying soils in accordance with their capabilities and in planning for soil and water conservation, including drainage and irrigation, a conference on permeability was held in February 1947 by Soil Conservation Service personnel and other interested workers. This conference was called for the purpose of reviewing and discussing the work that had been done in measuring the permeability of soils, with a view toward standardizing: (1) the procedure and equipment for measuring soil permeability by means of core samples, and (2) the procedure for estimating permeability from field clues.

In order to be able to interpret the data secured from laboratory measurements made on undisturbed soil cores, on the basis of field performance, many soil core measurements have been made on areas subjected to different cropping and management practices where runoff measurements covering a long period of years were available. Percolation rates based on core measurements have been compared with infiltrometer data and with draw-down measurements in drainage areas where water was pumped and measured from bored wells.

Extensive studies in the Southeastern Region show that data on water-table draw-down based on measurements in draw-down wells are especially helpful in evaluating permeability data obtained by means of soil cores taken from the same areas. By correlating the permeability data on these soil cores with draw-down measurements, the permeability findings may be projected over much wider areas.

At many of the sites where the soil-core, draw-down, and other quantitative permeability measurements were made, complete examinations have also been made of the soil profiles. Observations were made of such visible characteristics as type of structure; arrangement of structural aggregates; texture; root distribution; presence of cracks, wormholes, and other voids; quantity and distribution of organic material; compaction; presence of restrictive layers (bottlenecks or barriers); and color. An analysis of these observations suggested

that a system of field clues could be developed by which the permeability information could rapidly be extended to provide reliable estimates of permeability in other areas for which measurements were not available.

Fourteen different soil characteristics that affect the movement of water into the soil surface and its rate of percolation within the soil are now being used as the basis of field clues for judging permeability. These are listed and described under the section, ''Evaluating permeability on the basis of subsurface soil characteristics.'' Major characteristics that have been found to be highly significant in evaluating permeability are the type of soil structure, including the relationship between length of horizontal and vertical axes of the structural aggregates; the direction and amount of overlap of the aggregates; and soil texture. Other important characteristics that must be observed and recorded are: visible pores, compaction, and character of mineral clay. Additional characteristics and modifications of those listed herein will undoubtedly be added as investigations are extended. These field clues are making it possible for soil technicians to project the measured permeability rates of key sites to other areas. Their use markedly lessens the number of soil-core measurements that would otherwise have to be made.

The type of information secured from the combination of field and laboratory determinations is illustrated by *figures 1, 2, and 3, pages 4, 5, and 6*, showing the physical characteristics of four Missouri soils, along with a description of structure as judged in the field. It will be noted that the four soils differ widely with respect to mechanical composition, porosity, permeability rate, structure, and organic matter content, although they are all sandy loams. There is also a very marked difference in these characteristics at different depths of the same soil.

Many measurements covering a wide range of land management and use may be needed before the permeability of the soils in an entire problem area can be correctly judged. By the end of 1949, in the entire country, the Service had made core measurements of permeability for less than 2,500 soil horizons at 780 different sites *(table 1, page 7)*.

CLASSES OF PERMEABILITY

On the basis of available data, it appears that the most practical system of classifying soil permeability from a Nation-wide standpoint is one consisting of seven permeability classes, as follows:

Permeability class	Permeability index	Percolation rate in inches per hour through saturated undisturbed cores under ½-inch head of water
Very slow	1	Less than 0.05
Slow	2	0.05 to 0.2
Moderately slow	3	0.2 to 0.8
Moderate	4	0.8 to 2.5
Moderately rapid	5	2.5 to 5.0
Rapid	6	5.0 to 10.0
Very rapid	7	More than 10.0

Obviously, in some areas all seven classes will not be represented. All gradations, however, are needed in a national system. In planning certain erosion control practices, it may be advantageous to combine certain classes. On the other hand, it may be desirable to subdivide certain classes to provide detailed information needed in designing drainage systems or for other special purposes. Because of the wide variation in climatic and physiographic conditions as well as types of farming found in different parts of the country,

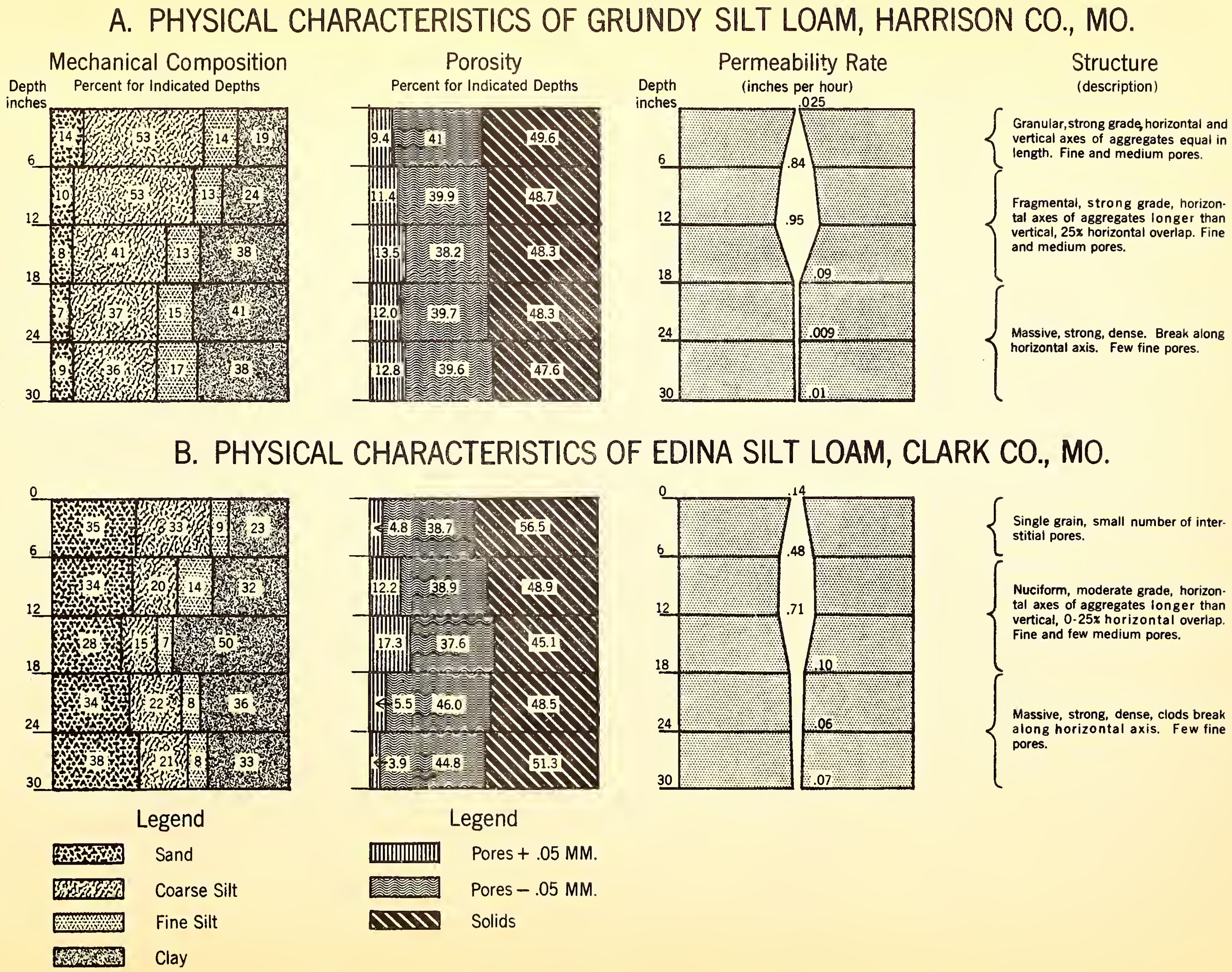

Figure 1.--Physical characteristics of Grundy silt loam and of Edina silt loam.

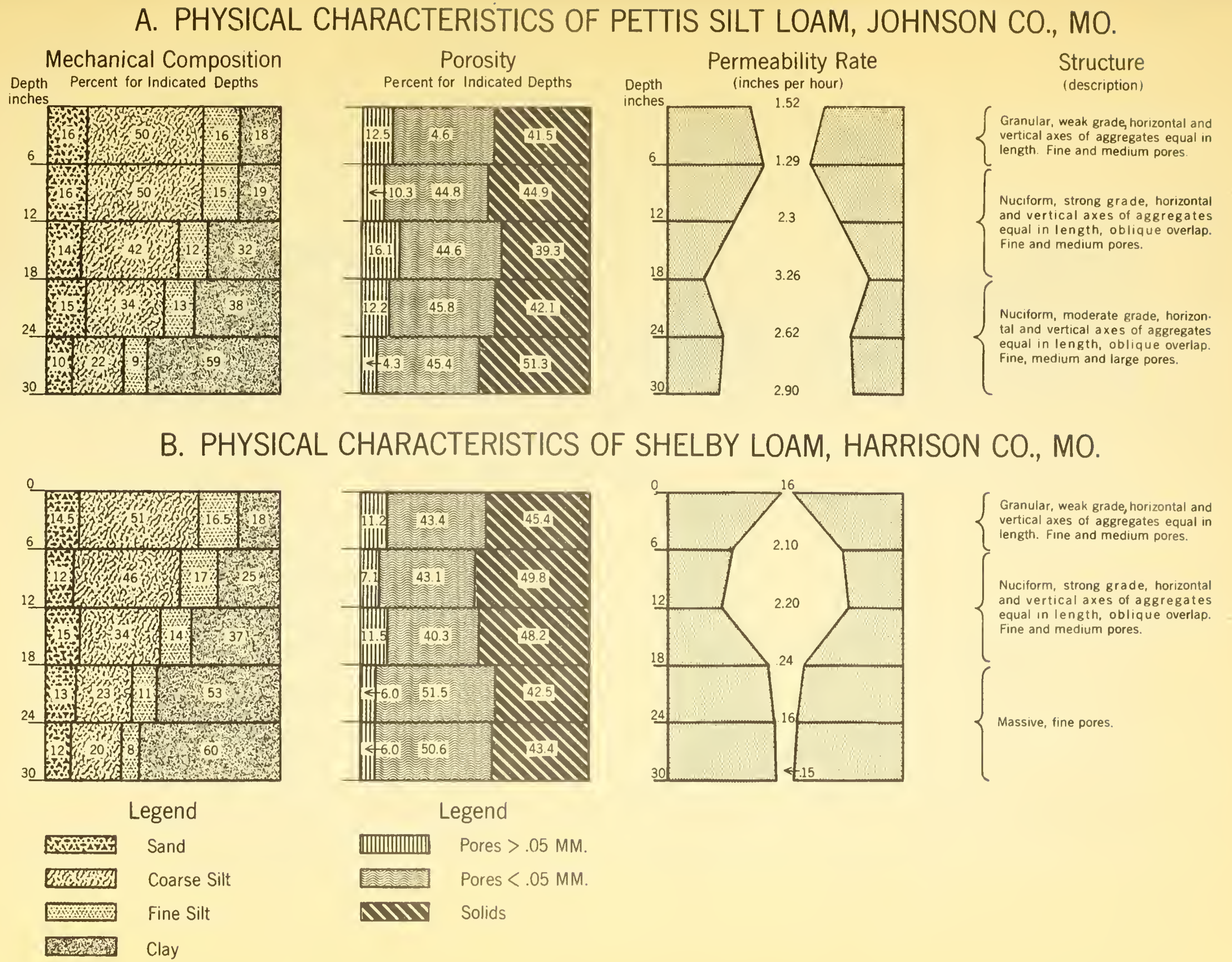

Figure 2. -Physical characterics of Pettis silt loam and of Shelby silt loam.

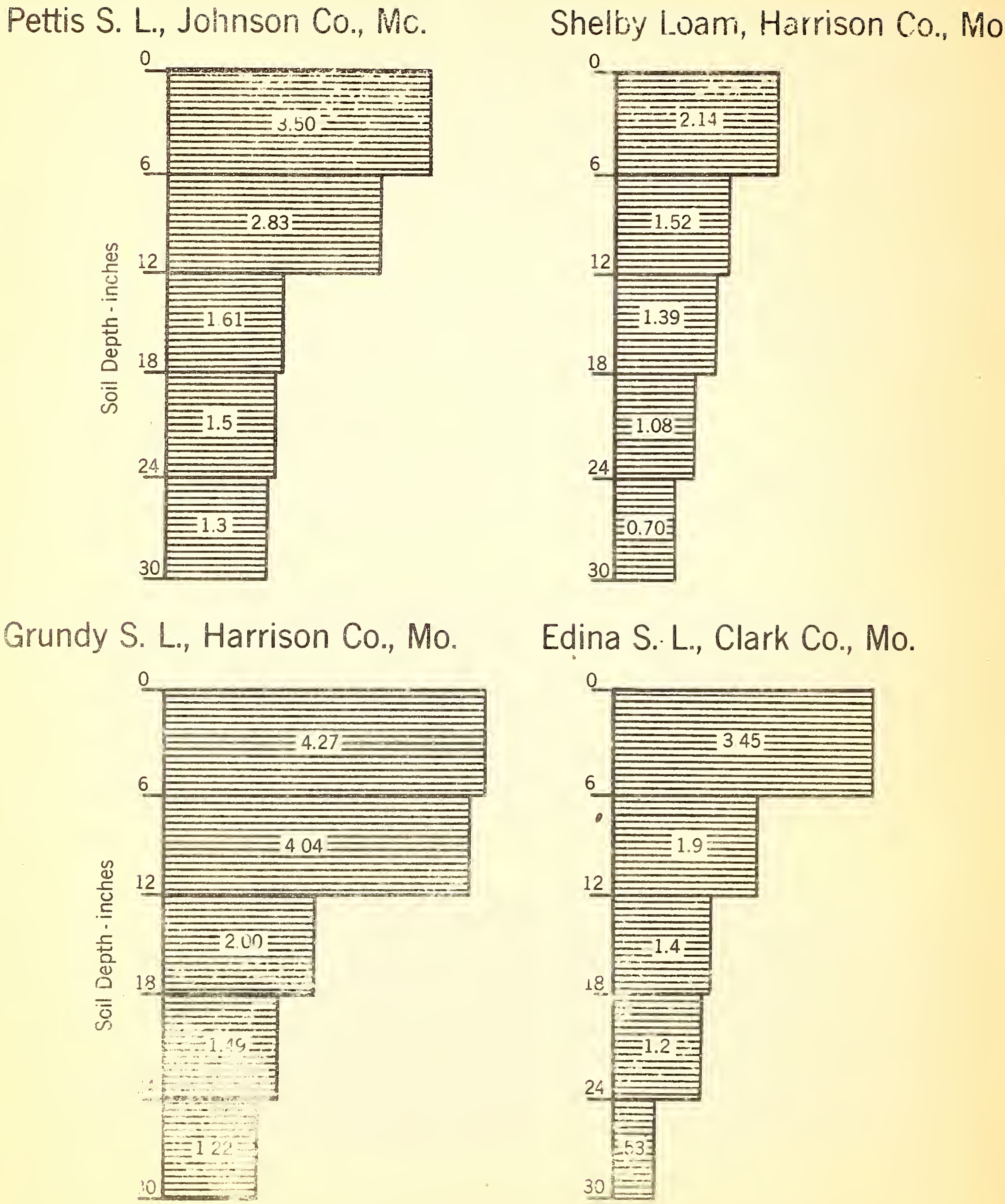

Figure 2.--Percent of organic matter at indicated depths for Pettis, Shelby, Grundy, and Edina silt loams.

Table 1.--*Progress of permeability determinations by means of core measurements as indicated by number of sites and horizons sampled to December 31, 1949*[1]

State and region	Sites	Horizons
	No.	*No.*
Region 1		
Connecticut	--	--
Delaware	--	--
Maine	1	3
Maryland	29	58
Massachusetts	--	--
New Hampshire	--	--
New Jersey	6	10
New York	30	60
Pennsylvania	10	26
Rhode Island	--	--
Vermont	6	18
West Virginia	--	--
Total for region	82	175
Region 2		
Alabama	24	79
Florida	60	207
Georgia	37	88
Kentucky	4	11
Mississippi	--	--
North Carolina	35	119
South Carolina	62	204
Tennessee	--	--
Virginia	164	459
Puerto Rico	--	--
Total for region	386	1,167
Region 3		
Illinois	62	264
Indiana	9	59
Iowa	--	--
Michigan	6	18
Minnesota	--	--
Missouri	13	77
Ohio	6	45
Wisconsin	4	36
Total for region	100	499
Region 4		
Arkansas	--	--
Louisiana	--	--
Oklahoma	--	--
Texas	--	--
Total for region	--	--
Region 5		
Kansas	5	9
Montana	15	34
Nebraska	4	36
North Dakota	--	--
South Dakota	--	--
Wyoming	--	--
Total for region	24	89
Region 6		
Arizona	7	28
Colorado	12	43
New Mexico	18	74
Utah	10	40
Total for region	47	185
Region 7		
California	24	272
Idaho	4	19
Nevada	--	--
Oregon	5	20
Washington	8	32
Total for region	41	143
Total, United States	780	2,458

[1] 3 to 6 replicates for each horizon on undisturbed soil cores.

the conservation practices for a given permeability condition may differ with localities. Future studies and experience may show that the limits of percolation rates specified for the respective classes may need to be modified slightly.

MEASUREMENT OF SOIL PERCOLATION RATES

Previous Methods and Their Limitations

A wide variety of equipment and procedures has been used in the past for measuring soil percolation rates. Cores have been taken of undisturbed soil in some locations by jacking and in others by driving. Comparisons of these two methods at several locations in Maryland, Illinois, and elsewhere disclosed little or no significant difference in the results obtained. In Virginia, Edminster et al[2] reported a small but significant difference which was not considered critical from the standpoint of field application. Since cores can be secured more easily and quickly by driving, this method has much in its favor.

Soil cores representing the soil surface can also be used under certain conditions to determine infiltration, or entrance of water at the surface. Many of the infiltrometers described for measuring infiltration are not well suited for extensive field use. The double-ring infiltrometer offers possibilities for measuring infiltration rates of soils under a sustained head of water. Neither this type of equipment nor the soil core supplies information on the infiltration rate of water from rainfall on the surface of bare soil. However, under conditions of good vegetal cover of sod or legumes or where crop residues are retained at or near the surface, the infiltration rates for water applied as assimilated rainfall differ little from those secured under a sustained head of ½ to 1 inch of water.

Permeability and pore-space measurements were made by Bendixen and Slater[3] on replicated soil cores from six subsoils in Maryland for the purpose of comparing soil cores saturated under open-air conditions and under vacuum. From a statistical analysis of the data these investigators concluded that on the basis of their trials the saturation of soil cores under vacuum results in so slight a difference in the percolation rate or in the volume of pores drained that for all practical purposes evacuation is unnecessary. Any advantage of saturation under vacuum appears to be more than offset by (a) difficulty of setting up and using the vacuum apparatus; (b) disturbance of the natural soil conditions; and (c) improbability of obtaining materially greater accuracy of measurements from the vacuum cores.

The size of soil cores used for determining percolation rates has ranged from a little less than 2 inches in diameter to 6 inches. The depth or length of cores covered a similar range. In addition, the ''post hole method''[4] has been used for determining the transmission rate of the different soil horizons and for locating the ''bottleneck'' or least permeable layer. Van Bavel and Kirkham[5] have described a method of field measurement of soil permeability using auger holes. A serious limitation of this method, as the authors state, is that it requires the presence of a water table, either perched or real, which preferably should not be too low. This means that in most locations only a few opportunities are available for measurement each year and in many locations the method is not applicable at

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[2] Edminster, T. W., Turner, W. L., Jr., Lillard, J. H., and Steele, F. TEST OF SMALL CORE SAMPLES FOR PERMEABILITY DETERMINATIONS. Prepared for presentation at 1950 meeting of Amer. Soc. Agron. and for publication in Soil Sci. Soc. Amer. Proc. 1950.

[3] Unpublished data contained in memorandum from C. S. Slater, Dec. 3, 1948.

[4] Vanatta, E. S., and Uhland, R. E. BOTTLENECKS OF THE SOIL. U.S.D.A. Soil Conservation Service, Upper Miss. Region, Milwaukee, Wisc. Mimeo. rept. No. III-2246, 22 pp. 1946.

[5] Van Bavel, C. H. M., and Kirkham, D. FIELD MEASUREMENT OF SOIL PERMEABILITY USING AUGER HOLES. Soil Sci. Soc. Amer. Proc. 13: 90-96. 1948.

any time.

No significant differences have been found in the data secured on 3 x 3-inch and 4 x 4-inch soil cores taken to depths of 3 feet on six soil types in Maryland. Sixty of the 3 x 3-inch soil cores could be taken in the same period of time and with much less bulky equipment than was required to take six of the 4 x 4-inch cores. By using commercial ice-cream cartons, the 3 x 3-inch cores can be transported more conveniently from the field to the laboratory. Such cartons are light, hold the 3 x 3-inch aluminum cylinders containing the soil cores snugly, and are available at a reasonable cost. Taking soil cores longer than 3 inches increases the danger in many soils of sampling parts of two horizons in a single core. For special studies of specific layers such as a plow sole, it is sometimes desirable to use three 3 x 1-inch cylinders instead of one 3 x 3-inch cylinder. These soil cores (each measuring 3 inches in diameter and 1 inch long) can be separated by using a fine piano wire strung on a hacksaw frame.

It has been observed that, for many soils, the rates of either percolation or pore-volume drainage based on soil-core measurements are markedly higher immediately after the cores are brought to the laboratory (initial determinations) than after the cores have remained in water 14 hours or longer or after saturation in a vacuum. Since irrigation water in actual farming practice is usually applied when there is a large moisture deficit, and since rains frequently occur when the soil is quite dry, it is desirable to ascertain not only the initial infiltration and percolation rates but also these rates after saturation. The difference between the initial and ''saturated core'' rates may indicate the extent to which the soil may be modified by cropping, drainage, and cultural operations. It may also indicate the moisture content of the soil that will permit the most effective penetration of irrigation water, etc.

Studies to date show that much additional and useful information about the soil can be collected simultaneously by making full use of the soil cores collected for percolation rate measurements.

Equipment

The equipment needed for measuring soil percolation rates and volume of pores drained, together with a detailed description of the core sampler and other special equipment, is given below. The quantities shown represent the approximate amounts of each item needed for making core measurements on a State-wide scale.

Item Number	Description	Quantity
1	Core sampler[8]	1
2	3 x 3-inch aluminum cylinders[8]	200
3	3 x 1-inch aluminum cylinders[8]	50 to 100
4	One-pint cylindrical ice-cream cartons[8]	216 to 235
5	20 x 24-inch tension plates[8]	1 or 2
6	Spigots for tension plates, as needed	1 or 4
7	Plastic screening, 20 inches wide	2 yards
8	Metallic window screening, 20 inches wide	2 yards
9	Rubber bands 1½ inches wide and 3½ inches long[8]	250 to 500
10	Transparent rubber tubing, 1/4-inch inside diameter	30 feet
11	Blotters, 19 x 24 inches, desk or photographic	10
12	Large circulating electric oven	1
13	Metal cans, 4 x 2 inches, to hold aluminum cylinders while drying in oven	50 to 100
14	Lids for cans (item 13) with 3/8-inch hole in center	50 to 100

[8] Sources of procurement for this specialized equipment can be supplied by Soil Conservation Service Research on request.

Item Number	Description	Quantity
15	1-quart glass fruit jars	30 to 50
16	Graduate, 100 cc	1 or 2
17	Graduate, 500 cc	1 or 2
18	Unbleached muslin, medium grade, cut in circular pieces 5½ inches in diameter	5 yards
19	Metal pans 3½ inches or more deep, to supply area of 800 square inches to accommodate 50 or more soil cores	800 sq. inches of area
20	Filter paper 2½ inches in diameter	500
21	Desiccators, 12 inches in diameter (if soil cores are to be evacuated)	3
22	Metal pitcher or glass beaker, ½ gallon	1
23	Thermometer, Centigrade, for checking temperature of water	1
24	Water supply comparable to rainwater for soils in humid section, or comparable to water used to irrigate in irrigation section	
25	Suction flasks, 500 cc, for tension plate	1 to 4
26	Spatula, knife, hacksaw	1 each
27	Rapid-weighing balance, Toledo type	1
28	A rack with 3 shelves arranged as stairsteps--each shelf to provide space for 10 jars--will prove convenient for this work. The principle of the Mariotte bottle may be employed to maintain a constant head of water on top of each soil core.	1
29	Scotch tape, 1 inch wide	1 roll

Description of Special Apparatus or Equipment

Item 1. Core sampler. *Figure 4, page 11,* illustrates the soil-core sampler parts and *figure 5, page 12,* its assembly and use for taking 3 x 3-inch cores. The steel cylindrical base of the driving assembly fits snugly into the upper shoe assembly. It is mounted on a 5/8-inch solid steel shaft a little more than 2 feet long. The shaft has a threaded handle at the upper end. A 14-pound steel cylinder, 3-3/4 inches outside diameter and 4½ inches long, with a 21/32-inch hole exactly in its center, is placed on the 5/8-inch shaft and acts as a driving weight to force the sampler into the soil. The hole in the cylinder is just large enough to allow the weight to slide easily up and down and fall freely. A rope handle attached to the weight makes it easy to raise the weight to any desired height. The cutting head or lower shoe assembly is so designed that practically all the impact of the falling weight is directed downward and outward. This permits taking the core with a minimum of soil disturbance. (The core sampler is being improved to facilitate the taking of cores below the plow depth without making an excavation.)

Item 2. An aluminum cylinder 3 inches long, with a 3-inch inside diameter and 3-1/4-inch outside diameter, fits inside the steel cylinder as indicated in *figure 4, page 11.* A small shock ring ½-inch wide fits on top of the cylinder to hold it in place. This aluminum cylinder serves as the container for the soil core.

Item 3. An aluminum cylinder 1 inch long, 3 inches inside diameter, and 3-1/4 inches outside diameter is placed on top of the 3-inch aluminum cylinder *(item 2).* It is secured with a rubber band *(item 9)* or 1-inch Scotch tape.

Item 4. One-pint cylindrical ice-cream cartons are used for transporting aluminum cylinders and soil cores from the field to the laboratory.

Item 5. Tension plate, 20 x 24 inches. For routine measurement of the volume of

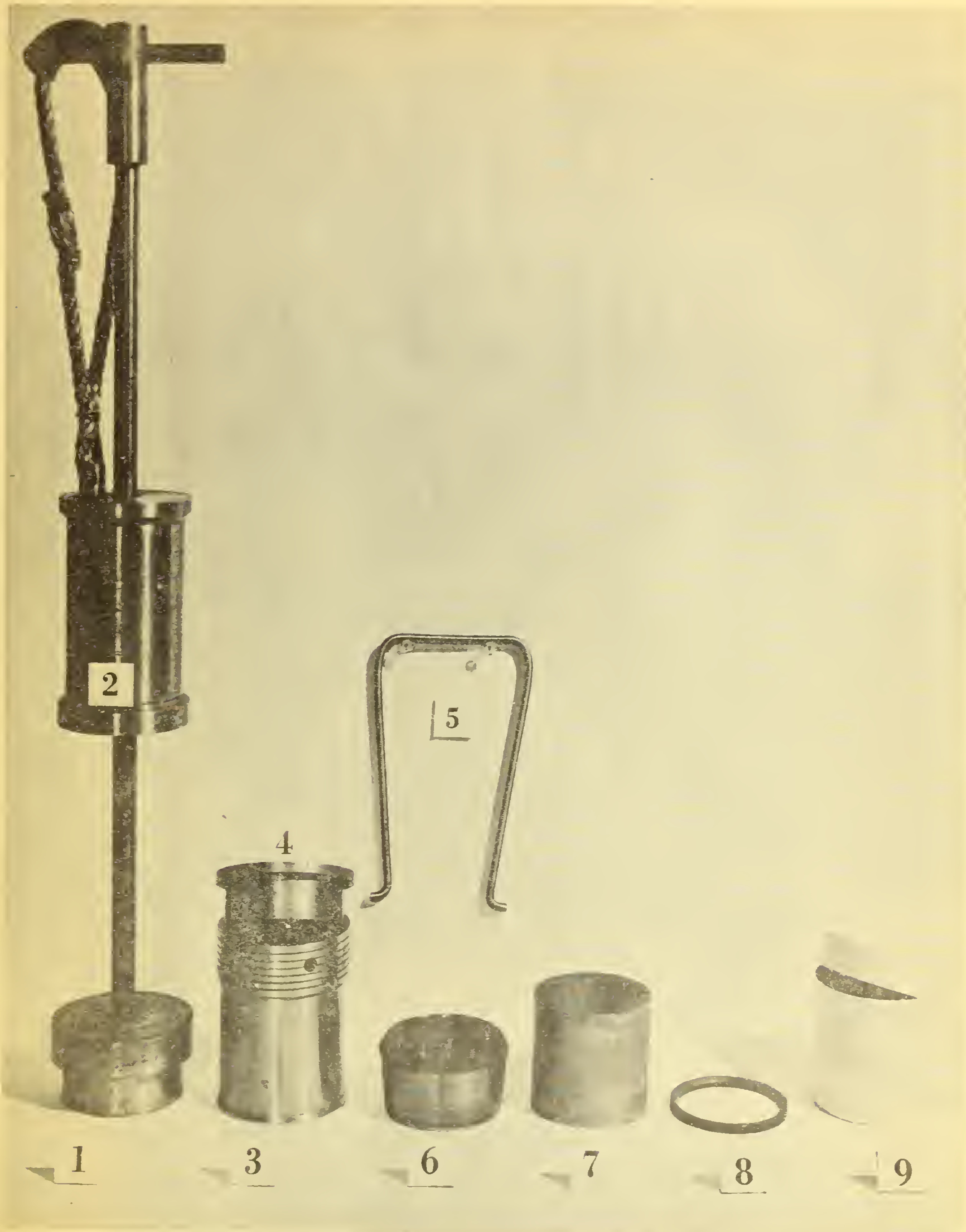

FIGURE 4.--Field soil-core sampler, assembly and use. (1) and (2) driving assembly; (3) and (6) upper and lower shoe assembly, respectively; (4) extra cylindrical head for use in taking cores with jack; (5) bale for pulling shoe assembly; (7) aluminum cylinder, fits into (3); (8) shock ring, fits on top of (7); (9) pint carton for transporting cylinder and soil core.

FIGURE 5.--Core sampler being assembled preparatory to taking sample. 3 x 3-inch aluminum cylinder fits into shoe assembly. The base of the driving assembly is inserted in the upper end of the shoe.

pores drained under 60 centimeters of tension, a metal or plate-glass plate with screen and blotters should be used.

(Thoroughly clean the glass or metal plate before placing the screen and blotters. Use only a plastic screen on a metal plate to avoid electrolysis. Either metallic or plastic screen may be used on glass plate. Cut the screen about 2½ to 3 inches shorter each way than the plate, and the blotter 1½ inches larger than the screen. Always allow ample space between blotters when they are fitted on the four quarters of a plate. Be sure to expel all air by rolling the surface carefully with a rolling-pin or a long smooth cylinder. Place a second blotter on top of the first and replace as often as pores become clogged. Cover the tension plate to prevent evaporation. Check the tension frequently to make sure that there are no leaks.)

Procedure

The procedure generally followed by the Soil Conservation Service in obtaining and using soil cores for permeability determinations needed in farm conservation planning may be described under four steps, as follows:

I. *Preparation of the site*
II. *Taking and preparing soil cores for laboratory determinations*
III. *Making initial determinations on soil cores before saturating overnight*
IV. *Making determinations on soil cores after saturating overnight*

I. Preparation of site

Sampling should be done when the soil is in good workable condition, not too wet nor too dry. Carefully remove all litter and vegetation from the site to be sampled. Take a minimum of not less than six replicates, three from each of two or more locations for each significantly different horizon. Replicated soil cores should be taken from each significantly different horizon below the surface layer wherever texture, structure, size of visible pores, etc. indicate probable differences in permeability. This may call for the sampling of from two to six horizons. For the topsoil or plow depth, sample either the 1- to 4-inch depth or the 2- to 5-inch depth.

Dig a pit to expose the respective layers to be sampled. Each horizon of the profile should be sampled separately; that is, no core should include parts of two different layers. Allow a minimum horizontal interval of 8 inches between the cores taken from the same pit and depth in order to prevent the outward impact of the sampler from compacting the soil of adjacent cores.

Where the concentric ring infiltrometer is used for measuring the entrance of water at the surface, the vegetation should not be disturbed. This also applies to the use of the rain simulator and infiltration measurements on soil cores representing the surface layer (0 - 3 inches).

II. Taking and preparing soil cores for laboratory determinations

(1) Drive the core sampler into the ground until the soil is about three-fourths of the way up in the ½-inch steel shock ring which rests on top of the aluminum cylinder.

(2) Loosen the sampler by rocking or rolling *gently* from side to side. Do not apply excess force. If sampler does not loosen easily, it may be dug out with a tile spade or pointed shovel.

(3) Remove the driving assembly. Loosen the cylinder containing the soil core by pushing gently on the soil at the bottom of the sampler. (A wooden plunger about 2 inches in diameter is a useful tool for this purpose.) For some soils it may be necessary to dig out a little soil from the bottom end to remove the cylinder and core.

(4) Cut off the protruding soil at the top and bottom of the cylinder so that it will fit into a 1-pint cylindrical ice-cream carton. It is preferable to let the soil protrude a little at each end of the cylinder and delay the final and exact trimming operation until the soil cores have been delivered to the laboratory. The soil may be trimmed with a knife or a hacksaw having a blade with sides that have been smoothed on an emery wheel. A fine piano wire may be used for some soils. The tool best suited will vary for different soils.

(5) Place the cylinder containing the soil core in the ice-cream carton, making sure that the core is not inverted but rests with its bottom end on the bottom of the carton. If necessary, reinforce the bottom of the carton with a fitted metal or pasteboard disk to provide a level base for the soil core to rest on. Store the cartons containing soil cores in a tight carrying case for transfer to the laboratory. As a precaution against possible jarring of samples while in transit in car or truck, the carrying case may be placed upon a thick foam-rubber mat. If the soil cores cannot be processed within 24 hours after they have been taken, an open 1-quart fruit jar containing saturated cotton or cotton waste should be placed at each end of the carrying case. This will prevent drying and shrinking of the soil cores for several days.

III. <u>Making initial determinations on soil cores before saturating overnight</u>

(1) Remove the aluminum cylinders containing soil cores from the cartons. Carefully trim both top and bottom so that the soil is flush with the ends of the cylinder. Cover the bottom of the cylinder with a circular piece of medium-weight muslin cloth and secure it with a rubber band.

(2) Place a 1 x 3-inch aluminum band or cylinder on top of the 3 x 3-inch cylinder containing the soil core *(fig. 6, page 15)*. Secure with a tight-fitting rubber band or 1-inch Scotch tape.

(3) Weigh cylinders with soil cores plus 1-inch aluminum bands.

(4) Set the assembled cylinders containing the soil cores in 4-inch moisture lids with circular screens 3½ inches in diameter, and place on top of 1-quart fruit jars arranged for convenient observation. Put a 2½-inch filter paper (bearing the same sample number as that stamped on the cylinder) on top of each soil core.

(5) Add 100 cubic centimeters of water (slightly less than 1 inch) on top of the soil cores and record the time of this initial application. Continue to add water so as to maintain a head of water of not less than ½ inch over each core.

(6) Record the time when the first drop of water falls from the soil core into the jar.

(7) Measure with a graduate the amount of water caught in the quart jar in 1 hour after the appearance of the first drop; or, if desired, record the time required for a given volume of water (350 cc, for example) to pass through the core and accumulate in the jar. The number of cubic centimeters of water caught in the quart jar in 1 hour, divided by a factor 115.7, gives the percolation rate in inches per hour.

FIGURE 6.--Core-sample assembly. Muslin at bottom of 3 x 3-inch aluminum cylinder prevents soil loss. The 1 x 3-inch aluminum ring at top is attached to permit maintaining a head of water. Both muslin and ring are held in place by heavy rubber bands.

(8) Decant and discard the water remaining on top of the soil cores. Wipe off any excess water adhering to the cylinder and cloth, and weigh the cylinders containing the cores immediately. Transfer them to a tension plate set at 60 centimeters of tension and allow them to drain for 60 minutes.

(9) Reweigh the cores at the end of 60 minutes. The difference in weight when placed on the tension plate and when removed represents the weight of water in grams, or volume of pores in cubic centimeters, drained from each soil core. (If the volume of water that drained from the replicates placed on each quarter of the tension plate or on a separate plate was measured, the weight of this water should agree closely with the total loss in weight of the soil-core replicates.)

IV. Making determinations on soil cores after saturating overnight

(1) Place the cores after weighing *(step III-9)* in a pan somewhat deeper than 3 inches. The pan should have a window screen on the bottom to keep the cores from touching the bottom of the pan. Slowly fill the pan with water to a depth slightly below the top of the soil cores. Record the temperature of the water. Cover the pan to prevent evaporation from the soil surfaces and allow the cores to saturate overnight (14 to 16 hours).

(1a. An alternate procedure is to evacuate the soil cores after weighing (step III-9) *by placing the cylinders in a vacuum desiccator at 19 inches of mercury suction for 10 minutes. Then, continuing the evacuation, allow the water to enter the desiccator slowly until the water level is just below the top of the cores. Allow the cores to stand approximately 30 minutes, then let more water enter the desiccator until the cores are covered with water. Release the vacuum and let the cores stand overnight or for 14 to 16 hours.)*

(2) Remove soil cores from pan or desiccator. Weigh and place in moisture lids on top of fruit jar as described under *step III-4*.

(3) Place 100 cubic centimeters of water on top of the cores. Record the time and maintain a head of water of slightly more than ½ inch over the core for 1 hour. Or, if desired, record the time required for a given volume of water to pass through the core and accumulate in the jar. Measure and record the water in the jar for a determination of the percolation rate. Decant and discard all the water that remains on top of the soil cores.

(4) Wipe off any water adhering to the side of the cylinders and weigh immediately. Transfer the cylinders to a tension plate set at 60 centimeters of tension *(as under step III-9)* and allow them to drain for 60 minutes.

(5) Reweigh the cylinders with soil cores at the end of 60 minutes. The difference in weight when placed on the tension plate and when removed represents the weight of water in grams or the volume of pores in cubic centimeters drained from each soil core as indicated under *step III-9*.

(5a. Pore-volume drainage. If information is desired on the volume of pores drained from cores representing different horizons in 5- and 15-minute intervals, provide each quarter of the tension plate with a hole and spigot or use a separate tension plate for the replicates from each horizon. If only the volume of pores that are drained in an arbitrary time is desired, use a plate with a single spigot. Attach a transparent rubber tube (equipment item 10) *to each spigot and place the other end of the tube in a separate suction flask which is provided with an overflow and set to provide a tension of 60 centimeters.)*

(6) Remove the 1-inch aluminum cylinder from the top of the 3-inch cylinder and the muslin cloth from the bottom of the soil core. Place the 3-inch cylinders, containing the soil cores, in drying cans 4 inches in diameter and dry them thoroughly in an electric oven at 105° Centigrade. Weigh and record the weight. (The soil cores may be removed from the aluminum cylinders and placed in moisture cans for drying if the cylinders are needed for taking more soil cores. This additional work can be avoided by providing an ample supply of cylinders.)

(7) Summarize the data on transmission rate, volume of pores drained, volume weight, etc. in tabular form, as illustrated in *table 2, page 18*, which gives data on a percolation study at Pullman, Wash. (Sampling at only two depths was considered to be adequate for this study since there was no great difference in the permeability rates for the topsoil and subsoil. A minimum of six replicates instead of three should have been taken for each horizon.)

(8) Calculations: The volume of the 3 x 3-inch core is 347 cubic centimeters. This figure is used to calculate the volume percentage of water in field cores, their volume weights, etc., as shown in *table 2, page 18*. A specific gravity of 2.65 was assumed for the soils to arrive at the calculated figure for volumes occupied by air and soil.

The percolation rate for the initial run the first day when compared with the percolation rate for the second day indicates the way percolation may change with time. The rate calculated from core measurements does not imply that a given soil under field conditions always takes up and transmits an equal number of inches of rain. These rates do, however, give a good idea of the expected performance of different soils and how the percolation rate may be expected to vary under different types of management and for rains of different duration.

The last column of *table 2, page 18*, represents the calculated percent of the cylinder that was occupied by air after the soil cores had remained in water overnight.

(9) Measure the shrinkage (both vertical and horizontal) of the soil in the cylinders after they have been oven-dried. Record the shrinkage to the nearest percent, using the conversion values indicated in *table 3, page 19*.[7]

(10) Record the number of effective pores in a broken cross section of each oven-dry core. (A technique for obtaining this information by the use of paper clips 1/20 and 1/40 inch in diameter is described in the Soil Conservation Survey handbook, Southwestern Region.)

EVALUATING PERMEABILITY ON THE BASIS OF SUBSURFACE SOIL CHARACTERISTICS

Field studies at more than 96 sites for which percolation measurements are available show that the permeability of different horizons below the surface layer can be evaluated with a fair degree of accuracy from field clues based on subsurface soil characteristics.[8] Recent investigations indicate that such clues apply equally well in other sections of the country provided suitable adjustments are made for differences in soil and climate. Thus, information obtained from detailed studies at control sites for which permeability data are available can be extended to other areas where soil characteristics are similar. Such a

[7] Charles H. Diebold, Soil Conservation Service, Albuquerque, N. Mex., reports that for soils in the Southwestern Region a shrinkage of 0 to 6 percent seldom affects percolation rates, 7- to 10-percent shrinkage is associated with moderate reduction in permeability, and 11-percent or more shrinkage with marked reduction.

[8] O'Neal, A. M. SOIL CHARACTERISTICS SIGNIFICANT IN EVALUATING PERMEABILITY. Soil Science 67 (5): 403-409. 1949.

Table 3. -Data on percolation rate, volume of pores drained, volume weight, and moisture content of soil cores from Pullman Soil Conservation Experiment Station - May 9, 1950 - Pullman, Wash.

ROTATION PLOT NO. 1 - WHEAT AFTER ALFALFA

Core No.	Depth	Impacts required to secure core	Time water penetrated core	Gain in wt. of percolated core over field core	Percolation rate: First day	Percolation rate: Second day	Volume pores drained in 1 hr. at 60 cm tension	Water in field core: By volume	Water in field core: By weight	Water in saturated core: By volume	Water in saturated core: By weight	Oven-dry weight of soil core	Volume weight of soil core	Water held per inch of saturated soil	Calculated volume occupied by soil	Volume of cylinder occupied by soil	Volume of cylinder occupied by air
	Ins.	No.	Minutes	Grams	Ins./hr.	Ins./hr.	Cm.	Percent	Percent	Percent	Percent	Grams	Grams	Inches	Cc.	Percent	Percent
331	2-5	14	0.5	68.4	7.26	3.37	32.6	30.0	25.0	49.7	41.5	415.5	1.20	0.497	157.8	45.5	4.8
332	''	15	7.0	77.7	3.92	.64	18.7	24.6	19.4	47.0	37.1	440.2	1.27	.470	166.1	47.9	5.1
333	''	14	1.0	75.1	6.53	.14	15.5	26.2	21.3	47.9	38.8	428.7	1.24	.479	161.8	46.6	5.5
Average	''	14.3	2.8	73.7	5.90	1.38	22.3	27.0	21.8	48.2	39.1	428.1	1.24	.482	161.6	46.6	5.2
334	11-14	50	1.0	45.0	7.26	2.42	16.8	29.4	2'.3	42.4	30.7	478.7	1.38	.424	180.6	52.0	5.5
335	''	42	1.0	47.9	6.91	1.04	14.3	27.8	19.9	41.6	29.7	485.5	1.40	.416	183.3	52.8	5.6
336	''	53	3.5	36.2	2.32	.26	11.8	31.4	22.0	41.8	29.3	495.0	1.41	.418	186.8	53.8	4.4
Average	''	48.3	1.8	43.0	5.50	1.24	14.3	29.5	21.1	41.9	29.8	486.4	1.40	.419	183.5	52.9	5.2

ROTATION PLOT NO. 3 - WINTER WHEAT AFTER FALLOW

Core No.	Depth	Impacts required to secure core	Time water penetrated core	Gain in wt. of percolated core over field core	Percolation rate: First day	Percolation rate: Second day	Volume pores drained in 1 hr. at 60 cm tension	Water in field core: By volume	Water in field core: By weight	Water in saturated core: By volume	Water in saturated core: By weight	Oven-dry weight of soil core	Volume weight of soil core	Water held per inch of saturated soil	Calculated volume occupied by soil	Volume of cylinder occupied by soil	Volume of cylinder occupied by air
337	2-5	18	3.0	73.0	1.90	0.61	24.1	24.4	20.3	45.5	37.9	416.3	1.46	0.455	157.1	45.3	9.2
338	''	20	4.5	66.7	1.26	.13	13.3	26.7	20.9	45.9	36.0	442.6	1.27	.459	167.0	48.1	6.0
339	''	14	2.0	75.1	[illegible].91	.55	22.7	19.9	15.7	41.6	32.7	441.2	1.27	.416	166.5	48.0	10.4
Average	''	17.4	3.2	71.6	3.36	.43	20.0	23.7	19.0	44.3	35.5	433.4	1.33	.443	163.5	47.1	8.6
340	14-17	56	1.0	39.7	.86	.45	5.4	28.3	20.4	39.7	28.6	481.0	1.39	.397	181.5	52.3	8.0
341	''	50	1.0	32.2	4.97	.55	9.7	30.6	20.9	39.9	27.2	508.1	1.47	.399	191.7	55.2	4.9
342	''	52	1.0	27.9	4.84	.66	7.0	31.4	21.5	39.4	27.0	506.7	1.46	.394	191.2	55.1	5.5
Average	''	52.7	1.0	33.3	3.56	.55	7.4	30.1	20.9	39.7	27.6	498.6	1.44	.397	188.2	54.2	6.1

ROTATION PLOT NO. 5 - THIRD YEAR ALFALFA IN ROTATION

Core No.	Depth	Impacts required to secure core	Time water penetrated core	Gain in wt. of percolated core over field core	Percolation rate: First day	Percolation rate: Second day	Volume pores drained in 1 hr. at 60 cm tension	Water in field core: By volume	Water in field core: By weight	Water in saturated core: By volume	Water in saturated core: By weight	Oven-dry weight of soil core	Volume weight of soil core	Water held per inch of saturated soil	Calculated volume occupied by soil	Volume of cylinder occupied by soil	Volume of cylinder occupied by air
343	2-5	16	4.5	94.0	2.38	1.60	18.4	19.8	15.8	46.9	37.5	433.7	1.25	0.469	163.7	47.2	5.9
344	''	17	3.0	75.5	3.11	1.19	19.8	23.5	18.7	45.3	36.1	435.4	1.26	.453	164.3	47.3	7.4
345	''	14	2.5	90.6	6.18	3.93	17.0	20.6	17.8	46.7	40.4	400.5	1.15	.467	151.1	43.6	9.7
Average	''	15.7	3.3	86.7	3.89	2.24	18.4	21.3	17.5	46.3	37.9	423.2	1.22	.463	159.7	46.0	7.7
346	20-23	88	1.0	29.8	7.61	1.47	11.9	29.8	20.5	38.4	26.5	503.1	1.45	.384	189.8	54.7	6.9
347	''	60	1.0	23.7	1.86	.57	6.2	30.4	19.8	37.3	24.3	532.1	1.53	.373	200.8	57.9	4.8
348	''	53	1.5	34.5	4.97	.66	10.7	23.9	16.4	34.3	23.2	506.2	1.46	.343	191.0	55.0	10.7
Average	''	67.0	1.2	29.3	4.81	.90	9.6	28.0	18.9	36.5	24.6	513.8	1.48	.355	193.9	55.9	7.6

TABLE 3.--*Shrinkage percentage of soil cores after oven drying*[1]

Horizontal shrinkage (inches)	Vertical shrinkage (inches)										
	0.00	0.02	0.04	0.06	0.08	0.10	0.12	0.14	0.16	0.18	0.20
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
0.00	0.00	0.7	1.3	2.0	2.4	3.3	4.0	4.7	5.3	6.0	6.7
.02	1.3	2.0	2.6	3.3	4.0	4.6	5.3	5.9	6.6	7.3	7.9
.04	2.7	3.3	4.0	4.6	5.3	5.9	6.6	7.2	7.9	8.5	9.2
.06	4.0	4.6	5.3	5.9	6.6	7.2	7.8	8.5	9.1	9.8	10.4
.08	5.3	5.9	6.5	7.1	7.8	8.4	9.0	9.7	10.3	10.9	11.6
.10	6.5	7.2	7.8	8.4	9.0	9.6	10.3	10.9	11.5	12.1	12.8
.12	7.8	8.4	9.1	9.7	10.3	10.9	11.5	12.1	12.7	13.4	14.0
.14	9.1	9.7	10.3	10.9	11.5	12.1	12.7	13.4	14.0	14.6	15.2
.16	10.4	11.0	11.6	12.2	12.8	13.4	14.0	14.6	15.2	15.8	16.4
.18	11.6	12.2	12.8	13.4	14.0	14.6	15.2	15.8	16.4	17.0	17.5
.20	12.9	13.5	14.1	14.6	15.2	15.8	16.4	17.0	17.5	18.1	18.7

[1]Based on cylindrical cores 3 inches, inside diameter, and 3 inches long.

system also provides a means for using the information obtained at these sites in evaluating the permeability of soils with different characteristics.

In the beginning there was little factual information to guide the investigation of soil characteristics significant in evaluating permeability. Casual observations of permeability had been made in connection with the mapping of soil types, but these were not highly reliable. A more scientific approach based on experience gained in determining soil texture seemed advisable. For exampl :, for practical purposes soil texture can now be fairly accurately and consistently mapped through the use of field clues. These clues are the outgrowth of years of study, in the course of which soil scientists have developed a sensitive touch with respect to soil characteristics that correlate with definite percentages of sand, silt, and clay in soil samples. Consequently permeability investigations began with a detailed study of the significantly different horizons below the surface soil and the recording of all discernible characteristics.

In developing the system for evaluating soil permeability on this basis, consideration was given only to horizons below the topsoil at sites for which percolation measurements on saturated cores were available. It was realized that infiltration (entrance of water into the immediate surface) and the permeability of the layer just below the surface inch were important, especially in irrigated sections. Nevertheless, the rapid changes that normally take place in the infiltration rates and in the permeability of approximately the upper 7 inches of topsoil under different cropping and management practices make it impracticable at this time to devise clues to permeability on the basis of topsoil properties. Permeability determinations have therefore been confined to the horizons of the subsoil and substratum where characteristics are more stable.

The following soil characteristics are being recorded and used as field clues at present. Additional clues may be added as the need for them develops and as their use and importance are worked out.

1. *Type of structure*
2. *Grade (stability) of structural aggregates*
3. *Relative length of horizontal and vertical axes of structural aggregates*
4. *Amount and direction of overlap of structural aggregates*
5. *Texture*
6. *Comparative ease and direction of natural breakage*
7. *Size and number of visible pores*
8. *Cracks and channels visible under hand lens*
9. *Character of clay minerals*
10. *Compaction*
11. *Size and shape of sand grains*
12. *Mottling*
13. *Organic material*
14. *Soluble salts*

Critical studies of over 2,500 horizons show that some soil characteristics are more important than others in judging soil permeability, and that the relative ease of water movement through the soil cannot be estimated on the basis of one characteristic alone. Fairly precise information is needed, for example, on the manner in which the structural aggregates are arranged in the soil. Consideration must also be given to such important characteristics of the aggregates as the relative length of their horizontal and vertical axes, the amount and direction of overlap of the aggregates (horizontal, oblique, or vertical), and their grade (durability or stability).

Finally, the investigator should weigh the factors that increase water movement against those that retard it. Due consideration must be given to the influence of visible pores,

type of clay, and stability of structural types under water. For example, the retarding effect of platy or fragmental structure with 25 to 50 percent horizontal overlap may be offset by the effect of large pores, cracks, and crevices, weak compaction, or kaolinitic composition of the clay. The modifying influences are discussed in further detail below:

1. Type of structure

Soil structure is a highly important characteristic. It refers to the condition of the soil material in which the primary particles like sand, silt, and clay are arranged and bound together through developmental processes into aggregates with definite shape. Aggregates may differ not only in type (shape) but also in class (size) and grade (durability or stability).

Ten types of structure are recognized: prismatic, columnar, cubical blocky, fragmental, nuciform, granular, crumb, laminar, phylliform, and squamose *(fig. 7, page 22)*. The last three are phases of platy structure and are given specific names for the sake of brevity in definition.

The identifying characters of the various structural types are summarized in *table 4, pages 24 and 25.*

Prismatic structure

This type of structure is characterized by flat-topped, prism-like aggregates. The vertical axes of the aggregates are longer than the horizontal axes; and horizontal cross sections are usually roughly hexagonal, square, or pentagonal. The macroprisms may break horizontally along secondary cleavage lines into cubelike or platelike microaggregates which may make identification of the structural type difficult unless its major characteristics are kept in mind. Occasionally the microaggregates are thin sections somewhat similar to fragmental structural types. The top and bottom faces of the small prismatic aggregates, however, are usually approximately parallel, unlike those of the true fragmental structure.

Columnar structure

Columnar structure differs from the prismatic only in having the tops of the prism-like aggregates rounded instead of flat.

Cubical blocky structure

Cubical blocky structure is roughly cubelike with horizontal and vertical axes about equal in length. In general, the six faces are rectangular; the surfaces may be rough. The blocks may either be stacked upon each other, resembling a prism, or offset horizontally. As in the prismatic and columnar structures, the offsets usually are at right angles with the vertical faces.

Fragmental structure

This type of structure is characterized by sharp acute angles and sharp ridges. The top and bottom faces are never parallel. The over-all shape of individual aggregates varies. The horizontal axis may be as long as the vertical or as much as four times longer.

Nuciform structure

Nuciform or nutlike aggregates are subangular or subrounded in shape. They are almost always obtusely angled, although one or two sharp angles may be present. Surfaces range from smooth to moderately rough. The vertical axis may be up to twice as long as the horizontal but, in general, horizontal and vertical axes are about equal in length.

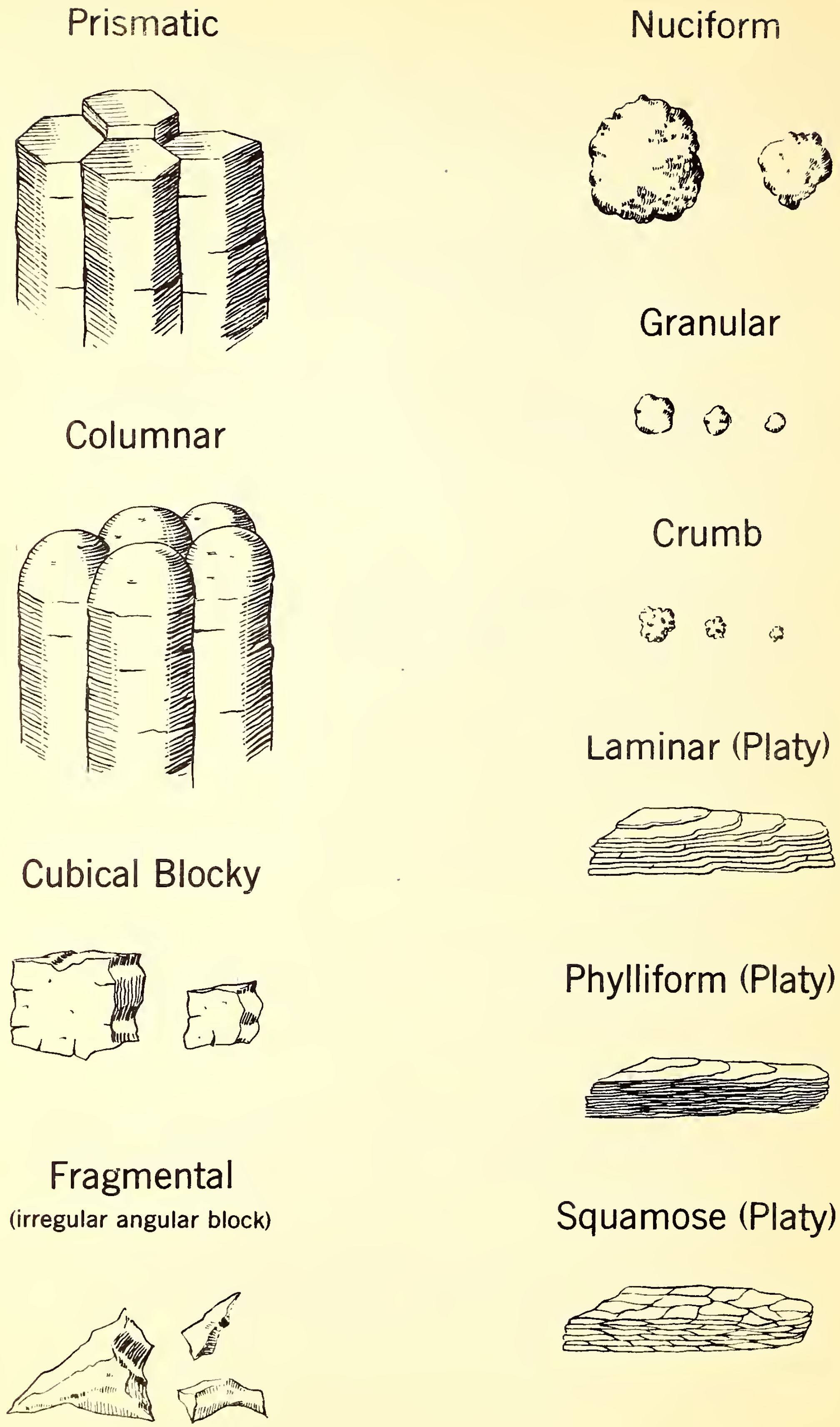

Figure 7.--Soil structural forms.

Granular structure

This type of structure is rounded or shotlike. It resembles the nuciform structure except that the granules are smaller, surfaces are smoother, and there are no angles. Usually there are no pits or cavities on the surface. Horizontal and vertical axes are of equal length.

Crumb structure

Aggregates are rough and irregular in shape, ranging from round to oblong. They are honeycombed and very porous, resembling crumbs removed from the interior of a loaf of bread.

Laminar (platy) structure

This type is characterized by continuous plates, usually 2 to 10 millimeters thick and arranged like the pages of a book. Horizontal axes are always much longer than the vertical ones. The plates are generally continuous.

Phylliform (platy) structure

This type differs from the laminar only in the greater thinness of plates, which are usually 1 to 2 millimeters thick.

Squamose (platy) structure

Squamose aggregates are scaly or flaky, with horizontal axes much longer than the vertical ones. Overlap is along horizontal or flatly oblique lines and usually ranges from 0 to 50 percent.

In classifying structural types, care must be exercised to determine whether the faces of the soil aggregates are developed surfaces or comparatively raw surfaces resulting from fracture of the soil mass. Developed faces usually have smoother surfaces and a finely traced pattern, apparently caused by the abrasive action of finely divided material dropped by water in its movement around the soil aggregates.

Each structural form may be considered to have (1) a macrostructure consisting of large primary aggregates easily seen when the soil mass breaks down, and (2) a microstructure consisting of the smaller aggregates that make up the larger bodies. Under proper moisture conditions, primary aggregates usually can be broken down into smaller and smaller aggregates of the same general shape. The size-range of aggregates in each subclass of the different structural types is given in *table 4, page 24 and 25.*

In classifying the type of structure, best results can be obtained when the soils are moist--neither too wet nor too dry. Under moist conditions, structural types usually stand out clearly. The macrostructure is sharply defined and is easily distinguished from the microstructure resulting from secondary breaks. As the aggregates dry, secondary cracks increase, the macroaggregates break into microaggregates, and it is often difficult to make the proper classification. Once the investigator becomes familiar with the soils of a given locality, he can distinguish and identify structural types even when soils are wet.

2. <u>Grade (stability) of structural aggregate</u>

Grade of structure refers to the stability or durability of the structural aggregates--weak, moderate, or strong. If the aggregates withstand jostling around in the hand

TABLE 4.--*Types, classes, grades, and descriptions of soil structural forms*

Type	Class	mm.	Grade (Durability or stability)		Description
Prismatic Vertical and horizontal cleavage; horizontal axes considerably shorter than vertical. Flat topped.	Very fine	10	Moderate	- Moderately fragile; moderate pressure required to break	Prism-like aggregates, flat topped. Tops and bottoms usually at right angles to vertical faces. Vertical faces usually well defined; surfaces vary from smooth to rough. Shape of the prisms when broken horizontally is dominantly roughly hexagonal but may be square, pentagonal, etc.
	Fine	10- 20			
	Medium	20- 50			
	Coarse	50-100	Strong	- Can be handled roughly without destruction	
	Very coarse	100	Very strong	- Will withstand very rough treatment	
Columnar Vertical and horizontal cleavage; horizontal axes considerably shorter than vertical. Rounded caps.	Very fine	10	Moderate	- Same as for prismatic	Prism-like aggregates, rounded caps. Vertical faces usually well defined; surfaces range from smooth to rough. Shape of the prisms when broken horizontally is dominantly roughly hexagonal but may be square, pentagonal, etc.
	Fine	10- 20			
	Medium	20- 50	Strong	- .... do	
	Coarse	50-100			
	Very coarse	100	Very strong	- .... do	
Cubical blocky Horizontal and vertical cleavage planes. Horizontal and vertical axes are more or less equal in length.	Very fine	5	Moderate	- Same as for prismatic	Usually six-sided, ranging in shape from cube-like to irregular blocky. In general, faces are rectangular and surfaces smooth to rough. The blocks either are stacked one above the other resembling a prism or show horizontal offsets. Vertical and horizontal axes are more or less equal in length.
	Fine	5- 10			
	Medium	10- 20	Strong	- .... do	
	Coarse	20- 50			
	Very coarse	50	Very strong	- .... do	
Fragmental (Irregular angular blocky)	Very fine	5	Weak	- Slight pressure required to break	Irregular in shape with acute, sharp angles and sharp ridges. Horizontal axis as long as the vertical or up to 3 to 4 times longer. Faces vary from smooth to slightly rough. Fragments usually vary as follows: when horizontal and vertical axes are equal they overlap along oblique lines; if horizontal axes are 3 to 4 times longer than vertical, the horizontal overlap will vary from 25 to 50 percent.
	Fine	5- 10			
	Medium	10- 20	Moderate	- Same as for prismatic	
	Coarse	20- 50	Strong	- .... do	
	Very coarse	50	Very strong	- .... do	
Nuciform (Nut-like)	Fine	5- 10	Weak	- Same as for fragmental	Subangular to subrounded with obtuse angles. There may be one or two sharp angles. Surfaces vary from smooth to rough. Some overlap of aggregates occurs usually along oblique lines.
	Medium	10- 20	Moderate	- Same as for prismatic	
	Coarse	20- 50	Strong	- .... do	
	Very coarse	50	Very strong	- .... do	

Granular	Very fine	1	Moderate	- Same as for prismatic	Somewhat rounded or shotlike; faces slightly rough. Usually there are no distinct faces, edges or angles. Usually shows no pits or cavities.
	Fine	1- 2			
	Medium	2- 5	Strong	- .... do	
	Coarse	5- 10			
Crumb	Very fine	1	Weak	- Same as for fragmental	Irregular rough shape; similar to a crumb from interior of bread loaf; usually quite porous.
	Fine	1- 2			
	Medium	2- 5	Moderate	- Same as for prismatic	
	Coarse	5- 10			
Laminar (platy)	Medium	2- 5	Weak	- Same as for fragmental	Paperlike plates arranged like pages in book with only an occasional vertical fracture. Plates generally continuous. Usually occurs in A-horizons of virgin or fallow soils and silt-pan layers. Often vesicular.
	Thick	5- 10			
	Very thick	10	Moderate	- Same as for prismatic	
Phylliform (platy)	Very thin	1	Very weak	- Very slight pressure required to break	Similar to laminar except that plates are thinner.
	Thin	1- 2	Weak	- Same as for fragmental	
Squamose (platy)	Medium	2- 5	Moderate	- Same as for prismatic	Usually scaly or flaky. The horizontal axes are much longer than the vertical, and the aggregates generally overlap along horizontal lines. Usually found in lower part of subsoil or in substratum.
	Thick	5- 10	Strong	- .... do	
	Very thick	10	Very strong	- .... do	

and subjection to considerable pressure between thumb and finger without breaking, the grade is strong. If they break easily and fall apart under slight pressure, the grade is weak. The grade (stability) should be determined on the basis of the durability of the aggregate when in moist condition.

The grade can be determined more effectively by the water-drop method.[9] Break off a small lump of soil one-half to one-quarter inch in diameter and note the number of drops of water required to slake it. The soil aggregate may be held on the end of a finger or preferably on a piece of wire screen. Drop the water from a height of 1 to 2 inches, using an ordinary eyedropper. Use the following scale to determine relative stability:

Relative stability	Number of drops to slake
Weak (unstable, slakes easily)	Less than 10 drops
Moderate (medium stability, only a slight amount of slaking)	10 to 25 drops
Strong (durable, does not slake)	More than 25 drops

Where necessary, this technique should be modified to fit locally prevailing conditions. Investigations at a number of sites in the western part of the Northern Great Plains and Southwestern regions, for example, show that when the soil slakes with less than 10 drops of water, the fine and medium pores generally have little effect on permeability. It was also observed that large pores, which ordinarily transmit water freely, are likely to become partially filled by silt and very fine sand particles.

3. Relative length of horizontal and vertical axes of structural aggregates.

Figure 8, page 27, and table 5, page 28, show the relationship that generally prevails between length of horizontal and vertical axes of structural forms, and the relationship of this and other factors to permeability. In prismatic and columnar structure the vertical axis is usually much longer than the horizontal; in cubical blocky, granular, and crumb structures the axes are about equal; and in laminar, phylliform, and squamose structures the horizontal axis is longer than the vertical. In fragmental and nuciform types, the proportions are variable. In fragmental, the horizontal axis may equal the vertical or be from three to four times longer. In the nuciform, the vertical axis may equal the horizontal or be as much as twice as long.

The relationships shown in *table 5, page 28*, may be modified by the size and number of visible pores, texture, type of clay minerals, presence of soluble salts, etc. For example, soils with prismatic structure may show faster percolation rates if the visible pores are large instead of fine or medium. Also, horizons with crumb structure and high sodium content usually have a slow or very slow percolation rate.

The relative lengths of horizontal and vertical axes are extremely important and should be carefully determined. For instance, fragmental aggregates having horizontal axes three to four times longer than the vertical and a horizontal overlap of 25 to 50 percent usually have either very slow or slow permeability. On the other hand, if the horizontal and vertical axes are more nearly equal in length and the horizontal overlap is less than 25 percent, the permeability is likely to be not less than moderately slow even if the texture is heavy. In nuciform aggregates, the permeability invariably is greater if vertical axes are longer than horizontal.

[9] HUTCHINGS, T. B., and DIEBOLD, C. H. FIELD CLUES FOR DETERMINING SOIL PERMEABILITY. Handbook on Soil Conservation Surveys. U. S. Soil Conservation Service, Region 6. 1950.

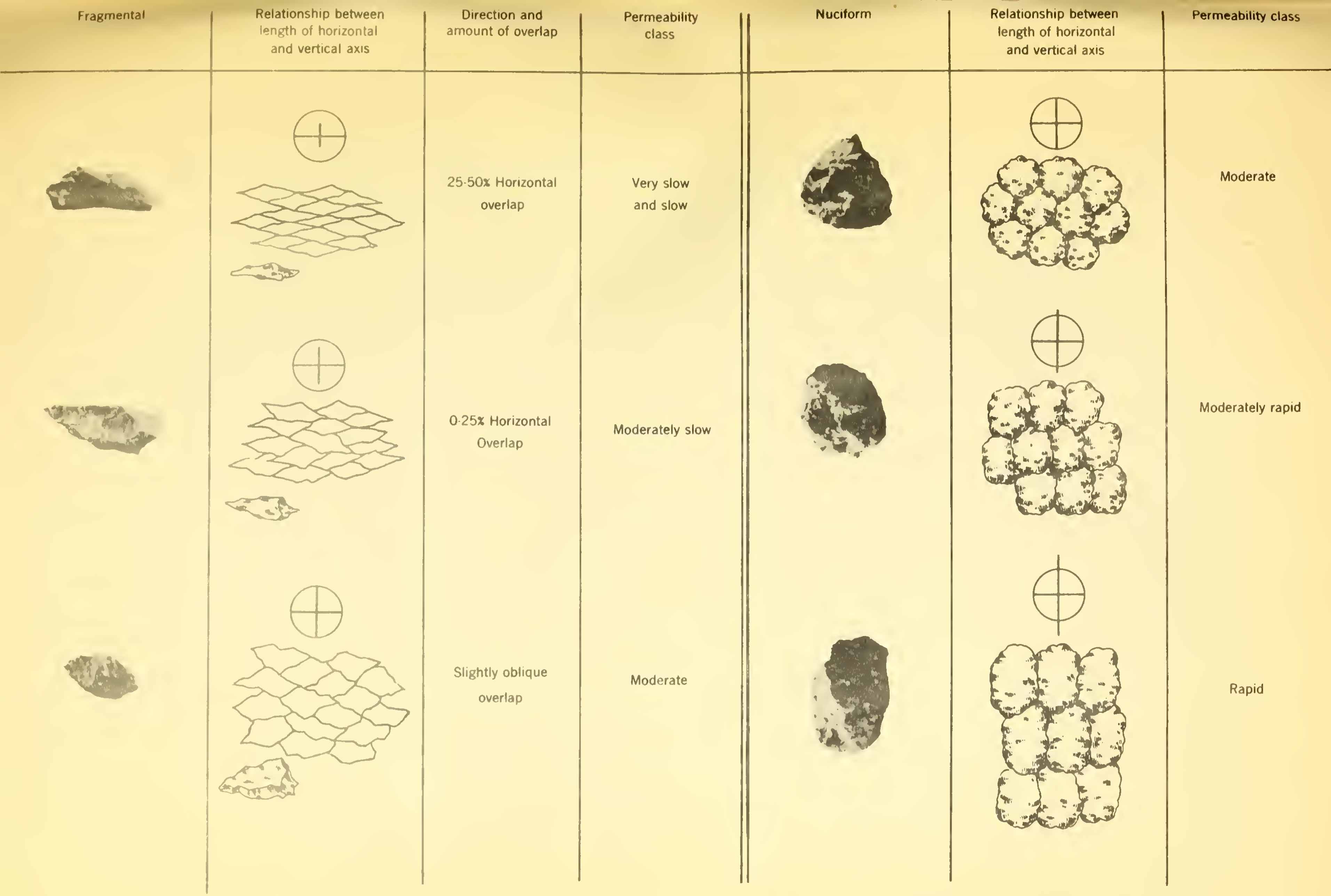

FIGURE 8.--Relationship between structural forms and permeability classes.

TABLE 5. -*Structure characteristics most commonly associated with each of the classes of permeability*

Permeability class	Type of structure	Relation between length of horizontal and vertical axes	Direction of overlap or offset	Amount of overlap
				Percent
Very slow	Massive	---	---	---
	Columnar	Vertical > horizontal	Horizontal	0 - 25
	Fragmental	Horizontal > vertical (4:1)	do	25 - 50
Slow	Prismatic	Vertical > horizontal	do	0 - 25
	Cubical blocky	Equal	do	0 - 25
	Fragmental	Horizontal > vertical (3:1)	do	0 - 25
	Squamose (platy)	Horizontal > vertical	do	25 - 50
Mod. slow	Prismat	Vertical > horizontal	do	0 - 25
	Cubical blocky	Equal	do	0 - 25
	Fragmental	Horizontal > vertical (1.5:1)	Flatly oblique	0 - 25
	Squamose (platy)	Horizontal > vertical	do	0 - 25
Moderate	Prismatic	Vertical > horizontal	Oblique	0 - 25
	Fragmental	Equal	do	Slight
	Nuciform	do	do	do
	Squamose (platy)	Horizontal > vertical	Flatly oblique	Slight
Mod. rapid	Nuciform	Vertical > horizontal (1.5:1)	Oblique	Slight
	Granular	Equal	do	do
	Crumb	Equal	do	do
Rapid	Nuciform	Vertical > horizontal (2:1)	Oblique	Slight
	Single grain	---	---	---
Very rapid	Single grain	---	---	---

4. Amount and direction of overlap of structural aggregates

Soil particles usually are arranged in the soil mass according to definite patterns. These patterns are useful in evaluating permeability because they reflect the amount and direction of overlap which in turn influences the length of channels through which gravitational water moves. For example, fragmental aggregates in which the horizontal axes are three to four times longer than the vertical ones usually have a 25 to 50 percent horizontal overlap. On the other hand, when vertical and horizontal axes are about equal the overlap is generally oblique, the channels are shorter, and percolation rates are faster. Nuciform, granular, and crumb structural types usually overlap along oblique lines, whereas the platy type always has longer horizontal axes than vertical and a horizontal overlap of 0 to 50 percent. Overlap in prismatic and columnar aggregates occurs mainly as offsets or protrusions that extend out from the prisms or columns at 90 degrees and dovetail into the adjoining protrusions.

The relationship of horizontal and vertical axes, the direction and amount of overlap, and the grade of structure can be appraised best by removing a large block of soil from the horizon being studied. Place it on the ground, bottom side down, and pull the mass apart along the vertical axes. Examine the vertical face of the fractured soil mass and note whether the protrusions have a definite pattern and whether their angles are sharp or rounded. If the vertical faces are smooth and somewhat slick and if some of the aggregates are offset horizontally at right angles to the vertical axes, the structural type usually is cubical blocky or prismatic. Rounded protrusions, on the other hand, indicate nuciform structure, and sharp angles and ridges suggest fragmental structure. Such clues, however, are not conclusive. As previously stated, the type of structure must be determined by a critical examination of the aggregates after the clods have been broken. The best procedure is to drop the clods on the ground and let them break under their own weight. The relationship between length of horizontal and vertical axes and the amount and direction of overlap of structural aggregates can be determined fairly accurately with practice.

In some horizons there may be both nuciform and granular structures, or some other mixture of structural types. Such mixtures may modify permeability. For instance, a mixture of approximately 75 percent fragmental and 25 percent nuciform usually indicates faster rates than fragmental alone, other characteristics being equal. The presence of all structural types should therefore be recorded, and notation made of the dominating structure.

Each horizon should be examined at a number of locations before a definite classification is made.

5. Texture

Texture is an important clue in evaluating soil permeability, but critical studies in various parts of the country have shown that when considered alone it is not fully reliable. For instance, although very slowly permeable horizons usually have heavy textures, not all heavy-textured soils are very slowly permeable. Also, loamy fine sands (light textures) with small percentages of silt and clay often have slower percolation rates than silty clays or clays (heavy textures). The influence of high silt content in retarding water movement has been noted in the Southwest where the percolation rate of many horizons with 60 to 65 percent silt has been found to be one entire permeability class below that of comparable horizons with from 25 to 30 percent silt. In that region a silt content of about 40 percent seems to mark a change in permeability class. This percentage may be different for other areas.

6. Comparative ease and direction of natural breakage

This factor is helpful in judging relative percolation rates. The ease and direction of natural breakage can be determined by removing a slice of soil about 3 to 4 inches thick with a tile spade. Holding the spade at an angle of about 45 degrees with the ground, tap it lightly on a rock or hard surface until the slice of soil cracks. Note whether breakage is horizontal, oblique, or vertical. Check the determination by selecting several lumps of approximately the same size and breaking them along horizontal and vertical axes by hand. Horizontal breakage usually indicates a modifying influence in favor of slower rates, other factors being equal. Where natural breakage is oblique or vertical, percolation rates in general are relatively rapid.

7. Size and number of visible pores

Visible pores include openings caused by roots, worms, and other animals. The size and number of such openings should be carefully recorded. The following pore-size classes are recognized:

Fine - 1/20 inch or smaller
Medium - 1/20 to 1/10 inch (about the size of the lead in an ordinary pencil)
Large - 1/10 inch or larger

Care should be exercised to determine whether the pores are continuous throughout the horizon or extend only a short distance and terminate in voids. In platy structure the surfaces of the plates frequently appear to be pierced by numerous fine pores which in reality are small solution pits. As previously mentioned, the effect of pore size on permeability may be offset by weak grade.

Field studies in various parts of the country show that it is possible to increase the number of visible pores in horizons below the surface by the introduction of deep-rooted crops. In South Carolina, the permeability rating of a soil with fragmental structure, 25 to 50 percent horizontal overlap, and high coefficient of shrinkage--properties that ordinarily indicate slow or very slow percolation rates--was increased to ''moderately slow'' in 2 years by planting sericea lespedeza. Kudzu on Cecil sandy clay loam perforated the subsoil to such an extent that percolation rates were greatly increased.

8 and 9. Cracks, crevices, and character of clay minerals

If structural aggregates in a dry or moist condition are broken, the exposed faces when studied with a 7- to 10-power hand lens may reveal a number of cracks and crevices. Some of these are large enough to transmit water if the clays are dominantly kaolinitic and do not swell greatly on saturation. On the other hand, if the clays are dominantly montmorillonitic the cracks will close completely when the soil is wet, and no water can get through. Therefore, a knowledge of the type of clay mineral is necessary for accurate evaluation of the effect of cracks and channels on the rate of water movement through the soil under saturated conditions. Such information is particularly important where heavy-textured soils are underlain by heavy-textured subsoils with prismatic structure derived from montmorillonitic clays. When dry, such soils crack extensively and permeability rates are high. But when saturated, the cracks close and little or no water gets through. Notation of cracks and crevices in sodium-saturated soils of the West is equally important.

10. Compaction

Differences in compaction or the appearance of fractured faces, with appropriate adjustments for soil textures, have been found useful in estimating percolation rates.

The term ''compaction'' refers to the manner in which the soil material between pores is packed together. It is classified as weak, moderate, strong, or very strong on the basis of the relative smoothness of the surfaces. Weak compaction is denoted by a sugary or fuzzy surface like that of cheesecloth; moderate compaction by a surface resembling that of linen cloth. Strong compaction is indicated by an artgum-like surface, and very strong compaction by a sheen resembling that of a shellacked surface. Comparisons of compaction apply only to soils of the same textural group since the exact appearance of the surface in each compaction class will vary for different soil textures. For this reason, the compaction of a fine-textured soil should never be compared with that of a heavy-textured soil.

The degree of compaction can best be determined by breaking a structural aggregate and observing the broken surfaces with a 7- to 10-power hand lens.

11. Size and shape of sand grains

In areas of sandy soils where the structure is dominantly single-grained, percolation rates can be more accurately estimated if consideration is given to size and shape of the sand grains. Ordinarily, interstitial spaces are larger and percolation rates faster when the grains are round and about the same size than when the grains are irregular in shape and of different sizes. When the grains are flat they tend to overlap in a horizontal direction like shingles, and percolation rates are lower.

Sandy horizons with relatively small percentages of silt, clay, or colloidal material usually have much slower percolation rates than the scarcity of such materials might suggest. Apparently the fine material fills the spaces between the sand grains and retards water movement.

12. Mottling

Mottling is a reliable clue to permeability if the reason for the mottling is known. Absence of mottling usually indicates moderate or more rapid permeabilities. On the other hand, moderately permeable to rapidly permeable horizons may be highly mottled where the soil is saturated by seepage from higher ground or where there is a water table caused by a barrier that restricts lateral flow.

13. Organic material

Available data indicate that organic matter in the form of humus is less effective than coarse, undecomposed organic materials in increasing percolation rates. Permeability measurements which have been made on horizons high in colloidal organic material indicate that percolation rates in such horizons may be less than where colloidal material is absent.

14. Soluble salts

The presence of sodium, through its influence on dispersion, retards the movement of water in some soils. It has been observed that medium-textured horizons with high sodium content usually have slow or very slow percolation rates. Recent studies show that the presence of relatively small percentages of sodium must be considered in evaluating permeability on the basis of field clues. Additional investigations are needed in areas where sodium is a problem.

FACTORS AFFECTING APPLICATION OF PERMEABILITY INFORMATION

Permeability ratings based upon soil core measurements apply directly only to that layer of the soil profile from which the soil cores are taken. For most soils the horizon with the slowest percolation rate is the one that limits the use and treatment of the land. The relative depth and position of each horizon or soil layer, along with the percolation rate of the respective horizon or layer, must therefore be taken into account in appraising the field performance of the soil in question.

Since soils vary widely in their response to land use, management, and treatment, and since the percolation rates for many soils are known to change with time and treatment, it is important that all these factors be considered in rating permeability for use in conservation planning.

Runoff data from all soil and water conservation experiment station farms show that both cropping and cultural operations have a marked effect on infiltration and runoff rates and therefore on permeability. Grasses and sod legumes are especially effective in promoting high infiltration. Crop residues, when retained on or near the soil surface, also favor high infiltration. Deep-rooted legumes favor rapid and deep penetration. Organic matter incorporated in the soil favors biologic activity, which makes for better aggregation and soil structure and favors permeability.

The effects of tillage operations on permeability vary widely for different soils in both amount and duration. Tilling some soils when too wet may have a lasting detrimental effect on both infiltration and permeability, whereas under proper conditions tillage may be beneficial.

Investigations have shown that cropping practices may greatly change the rate at which water will enter and pass through the soil. Studies of permeability on two soils in northeastern Illinois, for example, showed that percolation rates differed markedly with the crop grown *(fig. 9, page 33)*. In the 3''-6'' layer of Ashkum clay loam, percolation was 15 times more rapid with a clover cover than with corn; whereas in the lower layers the ratios were lower or even reversed. Drummer clay loam, on the other hand, had a higher percolation rate in the 3''-6'' layer when cropped to corn than when the land was in alfalfa pasture. At lower depths, percolation rates were higher for pasture than for corn. Van Doren and Klingebiel[10] report similar results for a large number of Illinois soils.

Differences in percolation rate were also noted at the Southern Piedmont Conservation Experiment Station, Watkinsville, Ga., where four different crops--cotton, sericea lespedeza, alfalfa, and kudzu--were grown on similar soils *(fig. 10, page 34)*.

Information on permeability under different mechanical and cropping treatments is particularly useful in planning erosion control measures for sloping land, where the amount of water that a given soil can transmit during a given rainstorm or succession of storms is greatly influenced by the condition of the soil, including kind and amount of soil cover.

Studies at Watkinsville, Ga., on the same soil cores as those used in determining percolation rates show that the crop had a marked effect on the rate at which pores drained for all depths within the root zone, as well as on the rate at which the soil transmitted water. There was a considerable difference in the cumulative volume of pores drained under 60 centimeters of tension during 5- and 15-minute intervals from cores representing different depths from fields in cotton, sericea lespedeza, kudzu, and alfalfa *(fig. 11, page 35)*.

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[10] Van Doren, C. A., and Klingebiel, A. A. PERMEABILITY STUDIES ON SOME ILLINOIS SOILS. Soil Sci. Soc. Amer. Proc. 14: 51-55. 1949.

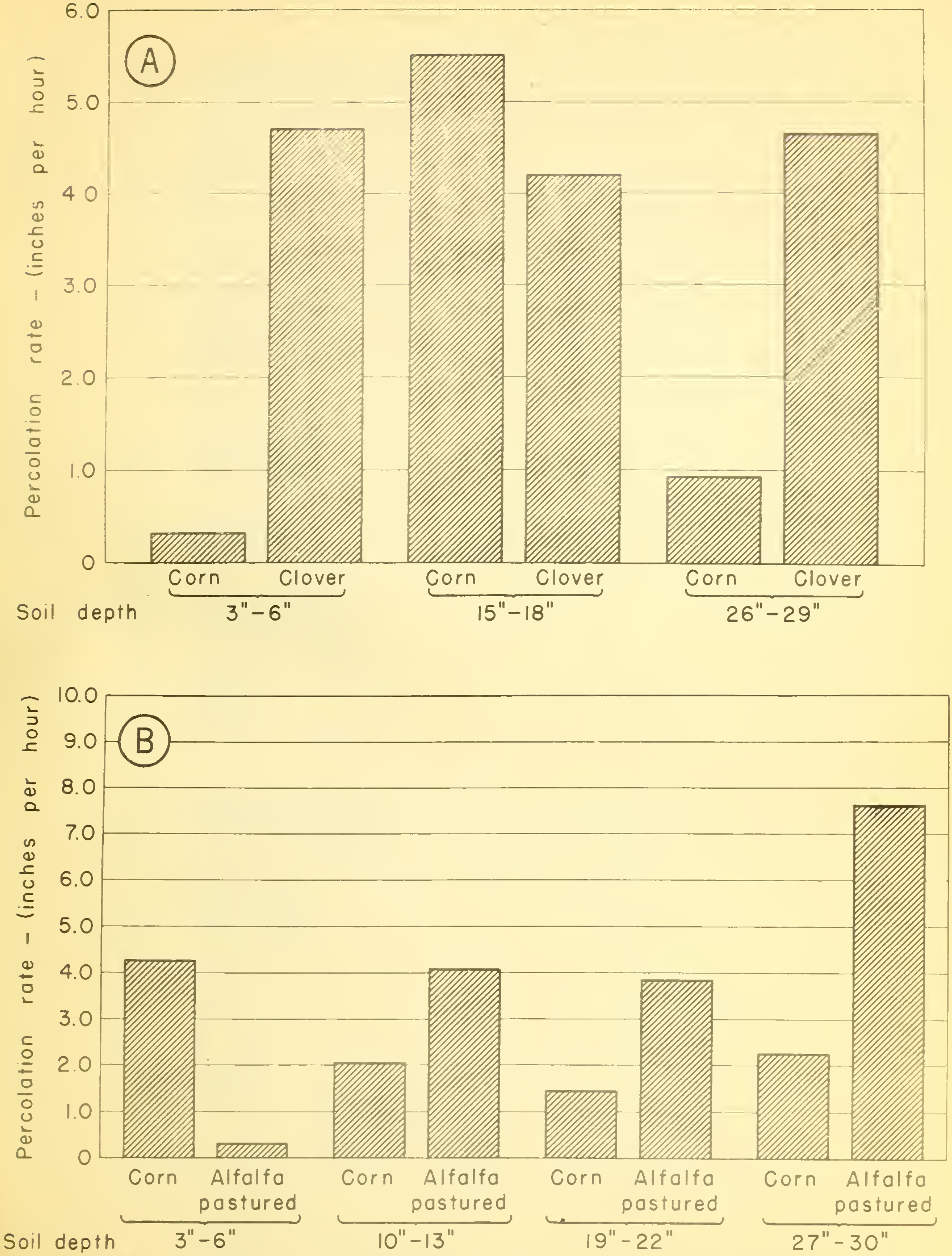

FIGURE 9.--Effect of crop on permeability of two northeastern Illinois soils. (A) Ashkum clay loam (B) Drummer clay loam.

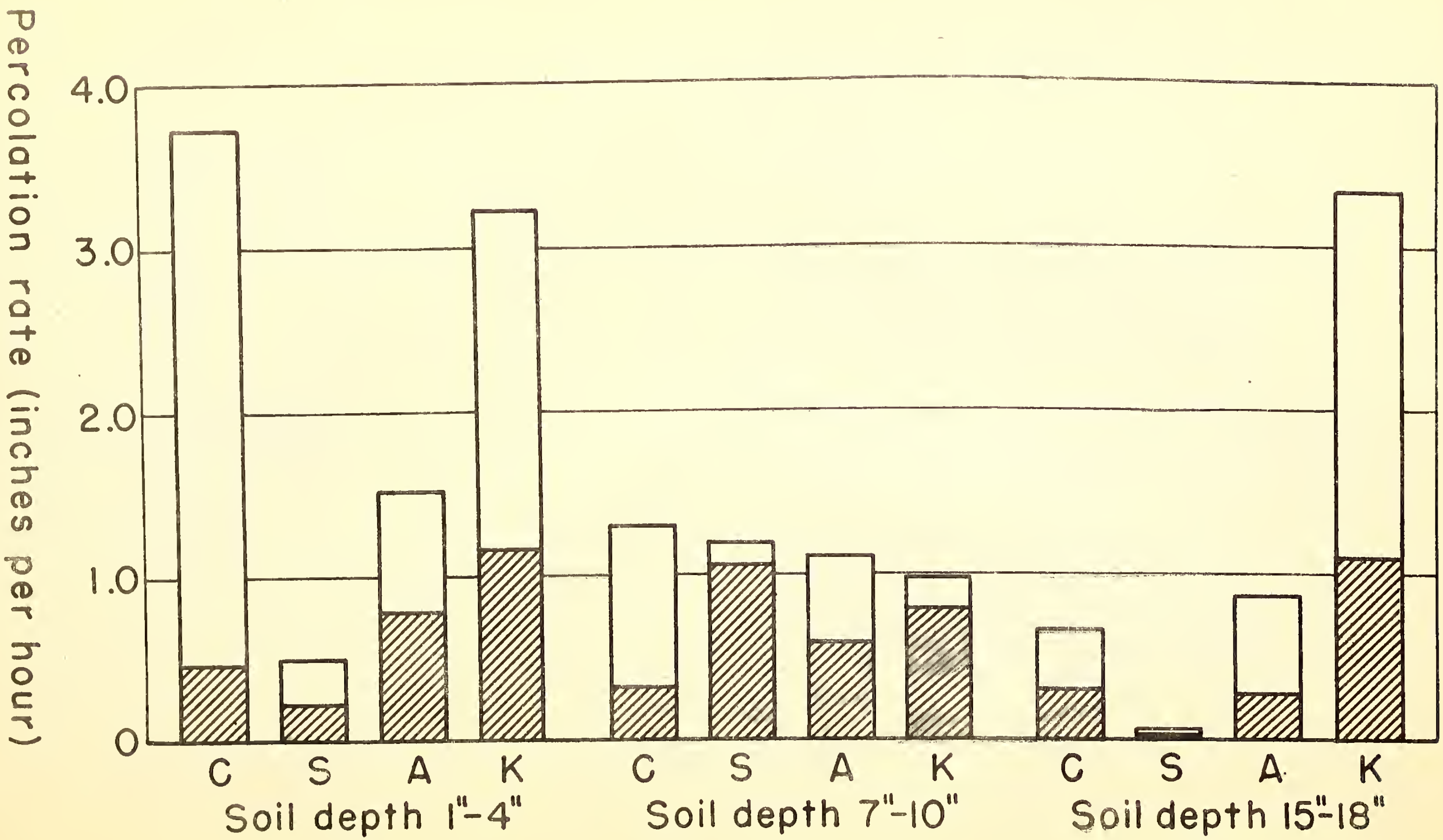

Figure 10.--Effect of crop on percolation rate for initial measurement and after saturating overnight. Shaded portion of columns represents percolation rate for saturated cores; shaded portion plus open column represents the initial percolation rate for the field cores. C - cotton; S - sericea lespedeza; A - alfalfa; K - kudzu.

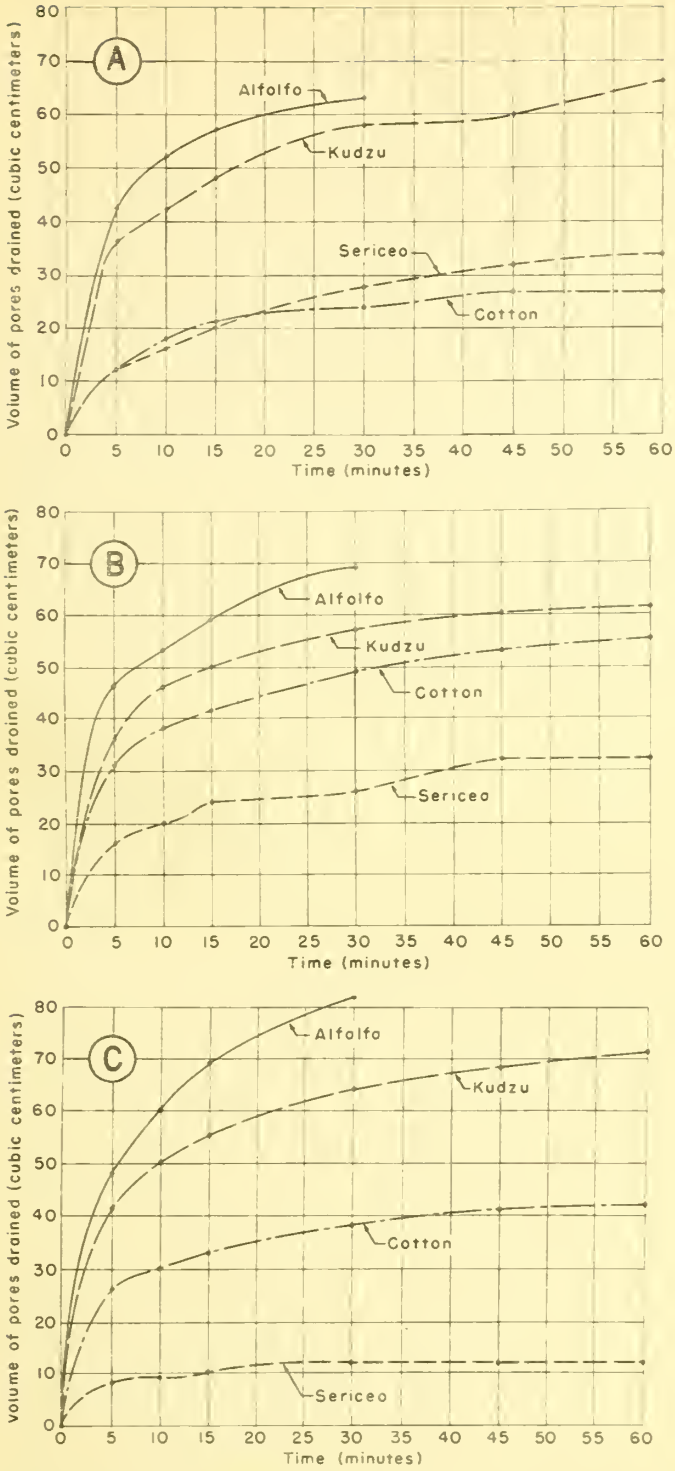

FIGURE 11.--Cumulative volume of pores drained at 5- and 15-minute intervals from soil cores taken at different depths from land in cotton, sericea lespedeza, alfalfa, and kudzu. (A) 1 - 4 inches; (B) 7 - 10 inches; (C) 15 - 18 inches.

These studies show that the percolation rates for saturated cores were much lower than the rates for nonsaturated cores for all crops and soil depths. The differences in percolation rate and pore drainage from soil cores for sericea lespedeza as compared with alfalfa and kudzu are difficult to explain. Further studies are needed on the relationships between crops, percolation, and pore drainage. Both types of measurements are needed to provide more complete information regarding soil-water relationships.

High percolation rates for some soil cores may be caused by wormholes or cracks in the soil. If cores show high percolation rates but low values for volume of pores drained, it is fairly certain that the high percolation rates are due to the presence of worm channels or cracks. These facts must be taken into consideration in appraising permeability.

During the investigations of subsurface horizons, many observations were made of characteristics that affect infiltration and the permeability of the upper part of the surface soil. For example, in Alabama a Pettis silt loam was studied at two sites: one in a stand of virgin timber; the other in a field that had been cropped to cotton and oats for nearly 30 years. The surface 4 inches of the virgin soil had a crumb structure and a percolation rate of over 5 inches per hour, whereas the poorly managed soil had laminar structure and a percolation rate of 0.39 inch per hour. Somewhat similar conditions have been observed in Utah, New Mexico, Texas, North Carolina, Ohio, and other States. These limited investigations indicate the need for more complete studies leading to the establishment of field clues significant in estimating infiltration and percolation rates for the plow depth of the soil.

The system of judging permeability presented herein will undoubtedly be improved and its application extended as more information becomes available and as the method is applied to a greater range of practical field problems.